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EFFECTIVENESS OF FOUR WATER COOLED UNDERGARMENTS AND A WATER COOLED CAP IN REDUCING HEAT STRESS

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

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~~20.~~ temperature and the temperature of the cooling water at the inlet to a water cooled undergarment. Isolation of the manikin surface from the hot environments ~~(Ta ≥ 35°C)~~ was provided by only a water cooled undergarment and the basic hot-weather clothing ensemble, no additional insulation, with its bulk and restriction to body movement, was used. Although these cooling garments did not, by themselves, completely isolate the manikin surface against heat gain from the hot environment, they did remove about one-half of the potential for heat gain from the ambient environment before the heat reached the manikin surface. The water cooled cap, which covered just the head (or only about 6% of the total body surface area) removed about 1/3 of the total metabolic heat production of a seated person.

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TECHNICAL REPORT

NO. T 23/76

EFFECTIVENESS OF FOUR WATER COOLED UNDERGARMENTS AND A WATER COOLED CAP IN REDUCING HEAT STRESS

by

G.F. FONSECA

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Natick, Massachusetts 01760

FOREWORD

Cooling the skin by conduction, using a garment cooled by cold water flowing through tubing, is an effective means of reducing the heat stress of personnel working in the enclosed crew compartments of aircraft or armored vehicles, in hot environments. Investigations of such cooling devices have usually used human volunteers, in controlled laboratory experiments in which the body, or part of it (e.g. the head), have been cooled. These studies frequently employ an insulating layer over those parts of the body cooled by the water cooled garment, to minimize the heat taken up from the hot environment. However, in most practical situations, the increased bulk, per se, of this additional insulation could impede cooling from sweat evaporation and also interfere with efficient task performance. The present experiment provides a direct physical evaluation of the efficiency of four water cooled undergarments, and a water cooled cap, both from precise measurements of the heat removed by the cooling water flowing in the tubing of these garments and from the reduction in the heat received from the hot environment at the wearer's skin surface; in these experiments the "wearer" was a heated, life sized copper man.

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ABSTRACT

The cooling provided by four different water cooled undergarments was directly measured on a heated copper manikin dressed in a basic hot-weather flight coverall, aircrew helmet, socks and black boots. This cooling, which represents absorption of the heat produced by the metabolic processes of the body plus that from the ambient environment in the cabin, was found to be almost directly proportional to the difference between the manikin skin temperature and the temperature of the cooling water at the inlet to a water cooled undergarment. Isolation of the manikin surface from the hot ambient environments ($Ta \geq 35\,^{o}C$) was provided by only a water cooled undergarment and the basic hot-weather clothing ensemble; no additional insulation, with its bulk and restriction to body movement, was used. Although these cooling garments did not, by themselves, completely isolate the manikin surface against heat gain from the hot environment, they did remove about one-half of the potential for heat gain from the ambient environment before the heat reached the manikin surface. The water cooled cap, which covered just the head (or only about 6% of the total body surface area) removed about 1/3 of the total metabolic heat production of a seated person.

EFFECTIVENESS OF FOUR WATER COOLED UNDERGARMENTS AND A WATER COOLED CAP IN REDUCING HEAT STRESS

1. INTRODUCTION

Heat stress in crew compartments of aircraft, armored fighting vehicles and ships is a continuing problem except when solved by environmental conditioning. Such a solution almost always involves a considerable power, weight, dollar, and added maintenance cost. Although certainly beneficial, adequate reduction of heat stress from extended exposures in excessively hot environments can rarely be accomplished by prior heat acclimatization procedures, or by dressing a crewman in minimal appropriate hot-weather clothing. The opposite clothing approach, i.e. adding additional clothing insulation to isolate the man from the environment, has been adopted for fire fighters (7). While effective for short periods, it can so increase the bulkiness of clothing as to restrict body movement and increase the wearers' heat production during work (6). Wyndham (10) recommended using 4.5 kg. of ice, frozen in a waistcoat, to provide body cooling for a group of acclimatized South African gold miners to enable them to work for four hours in the deepest mine shafts, where high temperatures and 100% humidities coexist. Recently, Konz (3) et al have suggested a similar approach using dry ice. The added weight of the ice was more than compensated for by the cooling benefit derived. The reduction of heat stress in high performance aircraft, where solar radiant heating (even without the surface friction heating at high air speeds) can make cockpit temperature intolerable (1,2), has long been accomplished by water cooled undergarments. Despite several useful reviews of this approach (4,5), comparative evaluations of the various water cooled undergarments from vigorous physical, rather than purely physiological or subjective measurements are seldom reported. This report presents a physical evaluation of four different water cooled undergarments and attempts to define some of the general guidelines for such items, using data obtained with a heated sectional manikin dressed in a standard hot-weather clothing ensemble, by itself and with each of these four different water cooled undergarments. The overall resultant heat removed (in electrical watt) by each of these individual water cooled undergarments, and the precise cooling to each covered section(s) of the manikin was measured. The latter cooling is analogous to the removal of the metabolic heat produced in the body. Thus the total cooling provided by a suit can be partitioned between heat removed from the body and heat removed from the ambient air. Because of the recent interest in head cooling devices (8,9), a soft cap fabricated from a water distribution material is included in this study of water cooled garments.

2. EXPERIMENTAL METHOD

The electrically heated copper manikin consists of six sections: head, torso, arms, hands, legs, and feet. This manikin was placed in a standing position in a large temperature controlled chamber (test area dimensions: length 5.8 m, width 3.9 m, and height 2.7 m); chamber air temperatures (Ta) studied covered the range from 35 °C to 49 °C. The heat transfer between the manikin surface and the cooling water flowing in the tubing of a water cooled undergarment (WCG) is measured as the electrical watt required to maintain the manikin surface temperatures (Ts) constant. The difference between this heat transfer from the manikin surface, and the total heat absorbed by the water during its transit from the inlet to outlet of the WCG represents the heat absorbed from the environment (plus perhaps a very small amount generated by friction within the tubing). The cooling inlet water temperature (Tw) was measured at the tubing entrance to the WCG. The temperature differences between the manikin surface and the cooling inlet water temperature (Ts-w), between the air temperature and the manikin surface temperature (Ta-s), and between the air temperature and the inlet water temperature (Ta-w) were also measured.

The four water cooled undergarments included: an Apollo type space suit (designated A) and British water cooled garment (designated B), both of which provided cooling over the torso-arms-legs sections of the manikin, but no cooling over the head, hands, or feet; a water cooled vest (designated V) which provided cooling only over the torso section; and a water cooled undergarment (designated T), consisting of tubing without any backing material, which provided cooling over all sections of the manikin except for the face. Nunneley (4) has presented some operating characteristics for these water cooled undergarments, over a range of cooling inlet water temperatures of 6.7 to 32 °C and water flow rates of 0.7 to 1.8 liters/min (l/min). These operating characteristics formed the basis for selecting the values of inlet water temperature and cooling water flow rate for this study.

The hot-weather clothing (designated the Basic Clothing Ensemble) consisted of an aircrew flying helmet, 1 pair of socks, 1 pair of black boots, and a lightweight flight coverall. This Basic Clothing Ensemble, worn by the manikin, contained no extra clothing items to reduce the potential for heat gain by the manikin from the chamber environment. However, for one experiment the chamber air temperature was controlled at the manikin surface temperature and under this condition the electrical watt called for by the manikin must equal only that heat removed from the manikin surface by the cooling water.

3. INSULATION OF THE BASIC CLOTHING ENSEMBLE AND THE BASIC CLOTHING ENSEMBLE WITH EACH OF THE WATER COOLED UNDERGARMENTS

The insulation values in clo units (1 clo = $0.155\,^{\circ}C\ m^2/w$) for the Basic Clothing Ensemble alone, and with each of the water cooled undergarments without water in the tubing, is given in Table I. These values were obtained with an average manikin skin temperature of about $33\,^{\circ}C$ in "still", $21\,^{\circ}C$ air in a climatic chamber. While the ensemble with the British WCG provided the greatest overall insulation (2.0 clo), the ensemble with the water cooled vest provided the greatest insulation over the torso section (2.9 clo).

4. EFFECTIVENESS OF THE INSULATION, PER SE, OF A WCG IN REDUCING HEAT RECEIVED AT A MAN'S SKIN FROM A HOT ENVIRONMENT

The decrease in the amount of heat received over a man's surface area simply by adding a water cooled undergarment to the Basic Clothing Ensemble when he is exposed to an environment hotter than skin temperature (e.g. Ta = $49\,^{\circ}C$) can be calculated from the insulation values (clo) in Table I. The effectiveness in reducing this heat gained from a hot environment, for a given water cooled undergarment, is essentially dependent upon the body surface area coverage and the thickness of a given WCG, and woul' be essentially independent of the tubing design over the body. Using the Basic Clothing Ensemble as the basis for comparison, the total heat received by a man from a hot environment is reduced by about 20% when either the British or Tubing WCG is added to the basic ensemble, 15% when the Apollo WCG is added, and 9% when the Water Cooled Vest is added. Although the Tubing WCG covers the entire body except for the face, it has no supporting material. Thus, the tubing covering the head and hands is directly exposed to the hot environment and, since it provides little increase in insulation, therefore has little effect on the amount of heat received by these areas from a hot environment. Apparently, the greater thickness of the British WCG over the torso-arms-legs area of a man is sufficient to compensate for the greater body area coverage of the Tubing WCG. The Water Cooled Vest, which only covers the torso, shows the least effect of all the WCGs' in reducing the total heat received by a man from a hot environment.

If one considers only the torso-arms-legs sections of a man (which is the area completely covered by the Apollo, British, and Tubing water cooled undergarments) the percentage reduction in received heat shows little difference from the percentage based on the total heat received, except for the British WCG ensemble which increases from 20% to 30%. Again, this appears to be the result of the greater thickness of the British WCG over the torso-arms-legs sections. If the area of heat exchange considered is further restricted to only the torso, the Water Cooled Vest ensemble, because of its greater thickness over the torso, compared with the other water cooled undergarments, shows the greatest decrease in heat received; about 33%.

5. EQUIVALENT INSULATION OF FOUR DIFFERENT WATER COOLED UNDERGARMENTS WORN WITH THE BASIC CLOTHING ENSEMBLE

The total cooling provided by a water cooled undergarment at the skin surface can be separated into two parts: the first part consists of the heat removed from the skin that is generated internally (i.e. metabolic heat) and the second part consists of the heat removed that is received at or en route to the skin surface from a hot environment. When the skin temperature is equal to the air temperature, all the heat removed from the manikin's skin surface by a water cooled undergarment is metabolic heat. However, as the air temperature increases, the heat that would be received from a hot environment at the skin surface increases, and this contribution to the total heat removed by a WCG increases. This latter contribution to the total heat removed by the cooling water is used to calculate equivalent insulation (clo) values of four different water cooled undergarments worn with the Basic Clothing Ensemble. These values, given in Table II, are based on an air temperature of 49 °C and an 18 °C cooling water inlet temperature to the WCG. Those sections of the manikin covered by a WCG show an increase in clo, compared with corresponding clo values in Table I, because the heat removed from the air around the tubing of a WCG tends to cool the microclimate around a man and reduce the heat received at his skin from a hot environment. This effectively increases the insulation over his skin. It can be seen that those sections not covered by a WCG have the same clo values in both Tables.

6. EFFECT OF A GIVEN WATER COOLED GARMENT/TUBING DESIGN IN REDUCING THE HEAT RECEIVED AT A MAN'S SKIN FROM A HOT ENVIRONMENT

The insulation values for each of the water cooled undergarments worn with the Basic Clothing Ensemble given in Table I are based on the insulation properties of a given WCG/ensemble per se. However, in Table II, the insulation values for those sections of the manikin covered by a WCG are modified by the action of the cooling water flowing in the tubing of a WCG so that the effective insulation of a WCG/ensemble is increased. By comparing the heat received at a man's skin, based on corresponding insulation values (clo) as given in Tables I and II, the effectiveness of a given WCG tubing design in reducing the heat received at a man's skin from a hot environment (Ta = 49 °C) can be determined. These calculations indicate that the most effective water cooled undergarment for reducing the total amount of heat received by a man from a hot environment is the Tubing WCG which completely covers the man except for his face; this WCG reduces the total heat gained by about 70%. Although the tubing, per se, provided little insulation against receiving heat by the head and hands (cf. Table I) when cooling water is flowing through the tubing the heat load on these exposed areas of the body is appreciably reduced (cf. Table II). The Apollo and British water cooled undergarments essentially cover the same body area; the British WCG reduces the total heat gained by about 38%, while the reduction with the Apollo is slightly less, about 30%. The Water Cooled Vest, which covers only the torso, shows the lowest reduction in total heat gain, about 7%.

When consideration of the heat received by a man from a hot environment is restricted to the torso-arms-legs, the British and Tubing water cooled undergarments reduce the heat gain over this area by about 60%; the Apollo WCG, about 50%; and the Water Cooled Vest, about 12%. Further restricting the body area considered to just the

TABLE I. **Baseline of Thermal Insulation (clo) Values for Four Different Water Cooled Undergarments, Without Water in the Tubing, Worn with the Basic Clothing Ensemble**

MANIKIN SECTIONS

ENSEMBLE/WCG	HEAD	TORSO	ARMS	HANDS	LEGS	FEET	T-A-L*	TOTAL
BASIC ENSEMBLE**	1.4	1.9	1.5	0.8	1.7	1.3	1.7	1.5
WITH								
APOLLO WCG***	1.5	2.5	1.9	0.9	2.1	1.3	2.2	1.8
BRITISH WCG	1.5	2.5	2.1	0.9	2.4	1.3	2.4	2.0
TUBING WCG	1.6	2.3	1.9	0.9	1.9	1.3	2.2	1.8
WATER COOLED VEST	1.4	2.9	1.6	0.8	1.7	1.3	2.0	1.7

*TORSO-ARMS-LEGS SECTIONS

**AIR CREW HELMET, SOCKS/BLACK BOOTS, COVERALLS

***SOCKS ATTACHED TO APOLLO WCG

TABLE II. Equivalent Insulation (clo) Values for Four Different Water Cooled Undergarments, Water Inlet Temperature of 18 °C, Worn with the Basic Clothing Ensemble, Based on the External Heat Gained at the Manikin Surface from the Environment, at an Air Temperature of 49 °C

	MANIKIN SECTIONS							
ENSEMBLE/WCG	HEAD	TORSO	ARMS	HANDS	LEGS	FEET	T-A-L*	TOTAL
APOLLO WCG (flow rate 1.4 l/min)	1.5	4.7	3.9	0.9	3.7	1.3	4.0	2.6
BRITISH WCG (flow rate 1.0 l/min)	1.5	9.8	4.6	0.9	5.1	1.3	6.0	3.2
TUBING WCG (flow rate 3.0 l/min)	7.4	6.9	4.8	33.7	5.1	28.0	5.6	6.5
WATER COOLED VEST (flow rate 1.0 l/min)	1.4	5.6	1.6	0.8	1.7	1.3	2.3	1.8

*TORSO-ARMS-LEGS-SECTIONS

TABLE III. Distribution of the Total Cooling Provided by a Water Cooled Undergarment

PERCENT OF TOTAL WATT OF COOLING

	MANIKIN SECTIONS					
	HEAD	TORSO	ARMS	HANDS	LEGS	FEET
<u>WATER COOLED UNDERGARMENT</u>						
APOLLO	—	31	20	—	49	—
BRITISH	—	22	25	—	53	—
TUBING	7	26	20	1	44	2
VEST	—	100	—	—	—	—
% MANIKIN SURFACE AREA	8	28	15	6	34	9

torso, the Tubing WCG reduces the heat received by about 65%, the Apollo and British WCGs' by 44% and the Water Cooled Vest by about 50%. These calculations show that the proportion of the total skin area covered by the cooling tubing is of primary importance in determining how effective a given WCG is in shielding a body from a hot environment.

The contribution of the "extremities" (i.e. head, hands, and feet) to the total heat received by a man from a hot environment increases in proportion to the reduction in the amount of heat received over those body areas directly cooled by a WCG. The extremities contribute about 60% of the total heat received from the environment when wearing the British WCG, 50% for the Apollo WCG, 37% for the Water Cooled Vest, and only 12% when the Tubing WCG is worn. Since the extremities include only about 23% of the total body surface area, the heat received via the extremities is in excess of their percentage contribution to the total body surface area for all WCG/ensembles except the Tubing WCG/ensemble. This WCG/ensemble reduces the contribution of the extremities to about one-half the value that would be expected if the heat received were uniform over the body.

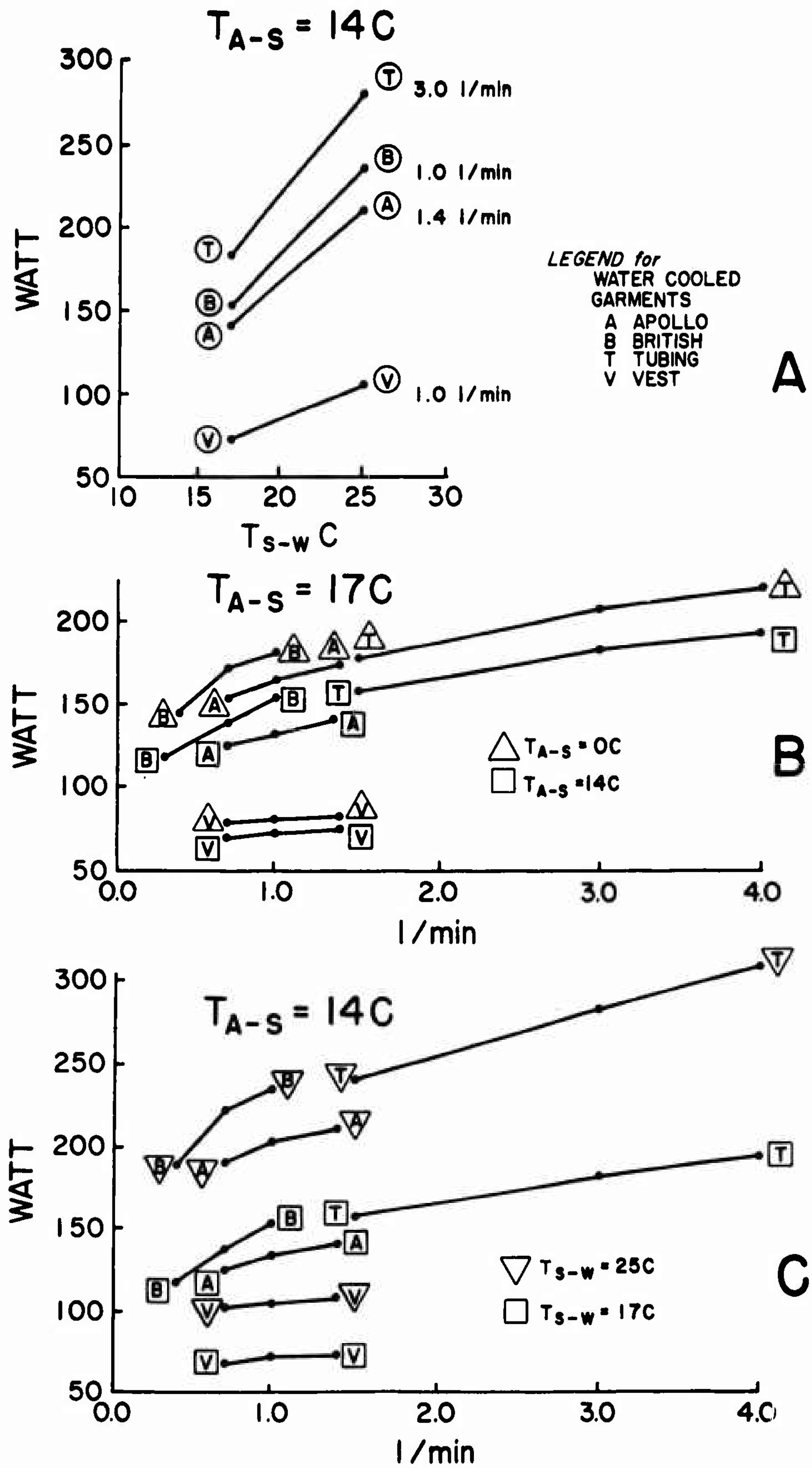
7. DISTRIBUTION OF THE TOTAL COOLING PROVIDED BY A WATER COOLED GARMENT

The percentage contribution of each of the six sections of the manikin to the total watt of cooling provided by a water cooled undergarment is given in Table III; these percentages are essentially the same as the percentages of the total length of tubing of a WCG calculated for the tubing covering a given section of the manikin. However, neither percentage is consistent with the respective area percentages for the six sections of the manikin, but rather reflect the designer's attempt to provide a greater proportion of the total cooling water to those areas of the body with the higher heat output, e.g. the muscle areas of the arms and legs. The greatest percentage spread between the Apollo and British water cooled undergarments (which essentially cover the same body area) is over the torso, with the Apollo WCG providing a greater percentage of the total cooling over this area of the body than the British WCG. However, all percentages show that the greatest cooling takes place over the legs and is in excess of the contribution of the surface area of the legs to the total surface area of the manikin (i.e., 34%). The distribution of cooling over the torso and arms is about the same for the British and Tubing water cooled undergarments, but the Apollo WCG provides a greater amount of cooling over the torso compared with the cooling it provides the arms. The cooling provided the extremities (i.e., head, hands, and feet) by the Tubing WCG consists of about 10% of the total cooling provided and this cooling is over about 23% of the total body surface area. The Water Cooled Vest provides all cooling over the torso and therefore its percentage equals 100% over the torso.

8. EFFECT OF INLET WATER TEMPERATURES AND COOLING WATER FLOW RATES ON THE HEAT REMOVAL PROPERTIES OF A WCG

The dependence of manikin heat loss on the temperature difference (Ts-w) between the manikin surface and the inlet water temperature, and the cooling water flow rate (l/min) of a WCG, is shown in Figure I for the four water cooled undergarments. Total heat removed (watt) are plotted as a function of temperature difference (Ts-w) between the manikin surface temperature and the inlet water temperature in the curves of part A of this figure. These curves show the increase in watt of cooling with increasing skin to water temperature gradient; the temperature difference (Ta-s) between the air and the manikin surface was kept constant at 14°C. The curves for part B and part C of this figure show the increase in watt of cooling with increasing water flow rate; however, since only a hot-weather coverall ensemble is worn over a WCG, the air temperature also effects the electrical watt supplied to the manikin; the difference between the manikin surface and inlet water temperature (Ts-w) is kept constant in part B of these figures; the temperature difference between the air and manikin surface (Ta-s) is kept constant in part C.

The increase in cooling with increasing temperature difference (Ts-w) between the manikin surface and cooling water inlet temperature is dramatic. This increase in cooling is almost directly proportional to the temperature difference; about 11 w/°C for the Tubing WCG, about 8 w/°C for both the Apollo and British water cooled undergarments and about 5 w/°C for the Water Cooled Vest. Thus, doubling this temperature difference will nearly double the heat transfer between a WCG and the manikin surface; but, of course, very low inlet water temperatures may be unacceptable to the wearer. On the other hand, although the curves for the water cooled undergarments all indicate that cooling increases with increasing water flow rate, the increase in cooling is not directly proportional to water flow rate. For example, for the Water Cooled Vest


T_{A-S} = 14C
300
250
200
150
100
50
WATT
10
15
20
25
30
T_{S-W} C
3.0 l/min
1.0 l/min
1.4 l/min
1.0 l/min
LEGEND for
WATER COOLED
GARMENTS
A APOLLO
B BRITISH
T TUBING
V VEST
A
T_{A-S} = 17C
200
150
100
50
WATT
0.0
1.0
2.0
3.0
4.0
l/min
T_{A-S} = 0C
T_{A-S} = 14C
B
T_{A-S} = 14C
300
250
200
150
100
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WATT
0.0
1.0
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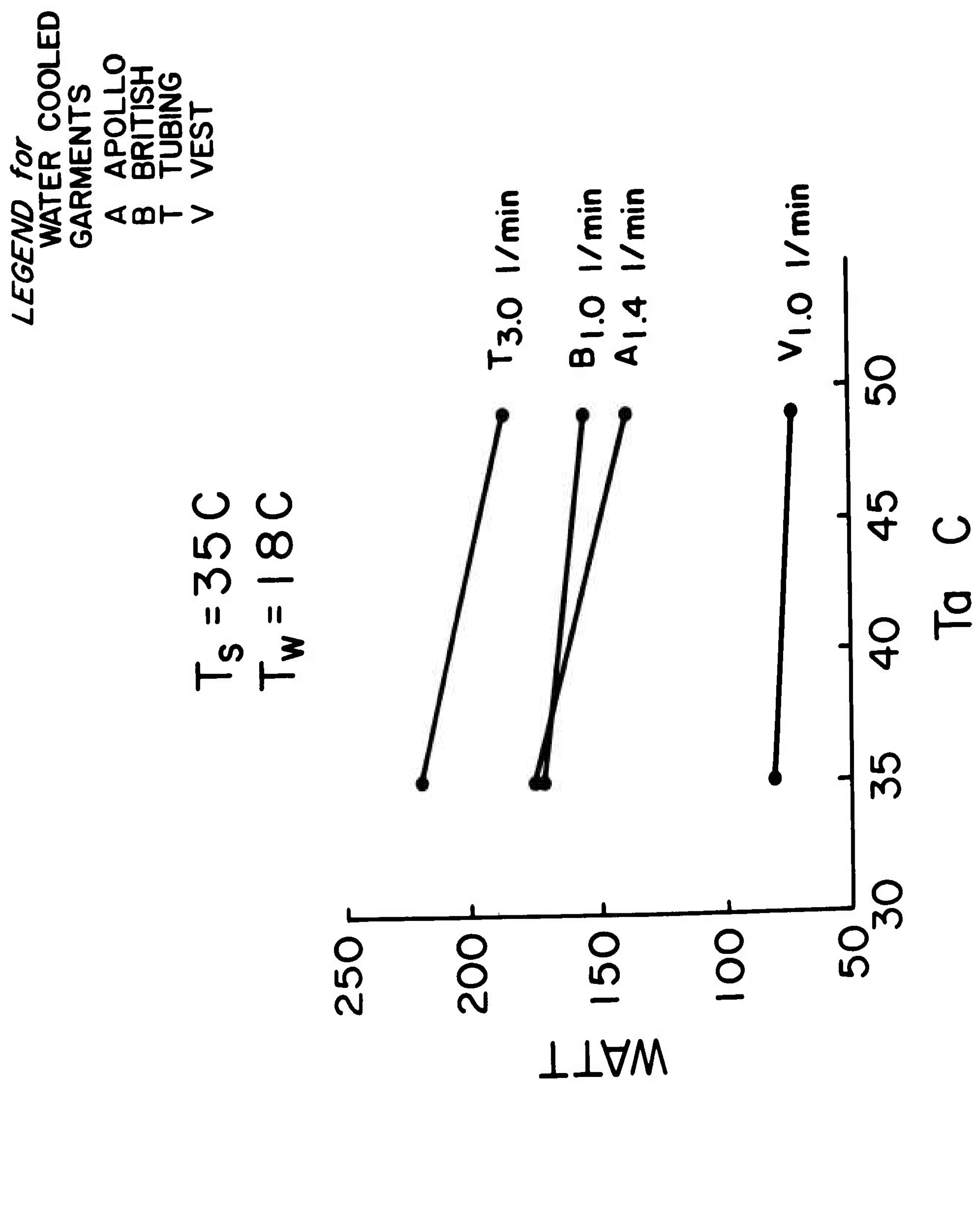
4.0
l/min
T_{S-W} = 25C
T_{S-W} = 17C
C


LEGEND for
WATER COOLED
GARMENTS
A APOLLO
B BRITISH
T TUBING
V VEST
Ts = 35C
Tw = 18C
T3.0 l/min
B1.0 l/min
A1.4 l/min
V1.0 l/min
WATT
250
200
150
100
50
30
35
40
45
50
Ta C

the cooling is almost independent of flow rate over the range 0.4 to 1.4 1/min.

9. EFFECT OF INCREASING AIR TEMPERATURE ON THE COOLING PROVIDED BY A WATER COOLED UNDERGARMENT

Figure 2 presents curves for the four water cooled undergarments showing the decrease in the electrical watt required to maintain the manikin surface temperature at 35 °C, with increasing air temperature. For each degree Celsius rise in ambient temperature above 35 °C, the cooling available to remove the heat produced by metabolic processes is decreased; with the Tubing WCG the decrease is 1.8 watt, with the Apollo WCG, 2.2 watt; with the British WCG, 1.5 watt; and with the Water Cooled Ves 0.6 watt. The clo values in Table I suggest that the surface of a body covered with the Apollo WCG ensemble should gain heat from the environment at the rate of 4.1 w/°C, the British WCG at the rate of 3.7 w/°C, the Tubing WCG at the rate of 6.4 w/°C, and the Water Cooled Vest by 1.1 w/°C. Comparing these values of w/°C calculated from the clo values in Table I with those obtained from the curves in Figure 2 suggests that the Apollo WCG absorbs about 50% of the potential for heat gain at the manikin surface from the environment, the British WCG about 60%, the Tubing WCG about 70%, and the Water Cooled Vest about 50%. This additional heat absorbed by the cooling water comes from the air surrounding the tubing of a given WCG. Thus, although these water cooled garments covering a surface do not completely isolate the surface from gaining heat from a hot environment, they do remove one-half or more of the potential heat gain.

10. ESTIMATE OF THE EFFECT OF INCREASING AIR TEMPERATURE ON THE REDUCTION OF BODY HEAT STORAGE USING A WCG

The effect of increasing air temperature on the reduction of body heat storage produced by a cooling garment can be estimated; the reduction in body heat storage is calculated in terms of the change in mean body temperature per hour by the equation:

$$S = mC_p\Delta T$$

where:

ΔT=Change in mean body temperature in degrees Celsius

m=Weight of the man in kg

C_p=Specific heat of body mass in w/kg

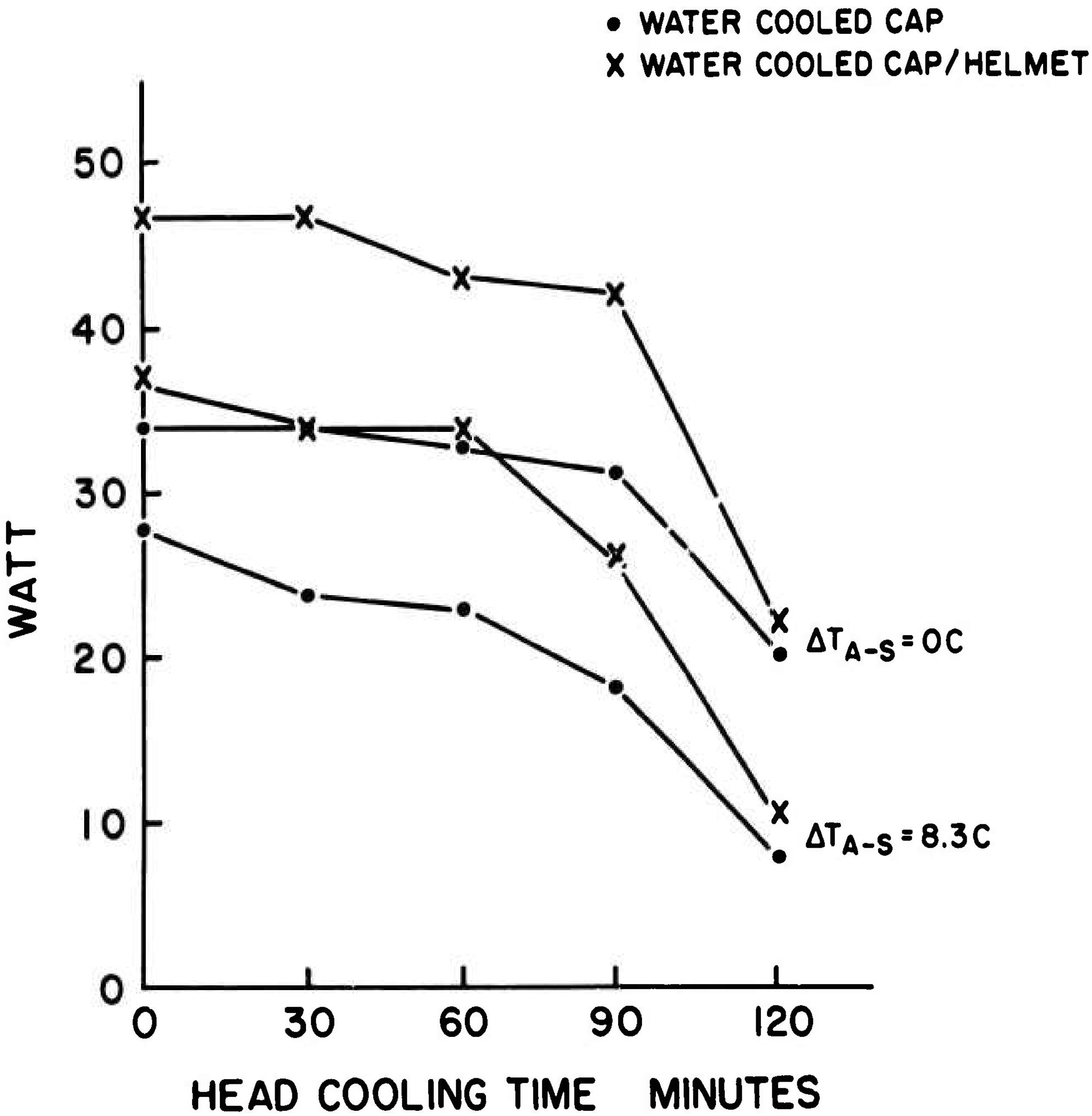
S=Body heat storage in watt

A value of 1.2 °C/hr has been calculated using this method for the decrease in mean body temperature based on the amount of cooling provided by an insulated vest containing dry ice (3). Using this method, the change in mean body temperature per hour was calculated for an increase in air temperature from 35 °C to 49 °C using the cooling curves shown in Figure 2. When the Apollo WCG was worn, the change in calculated mean body temperature per hour decreased from 2.6 °C/hr to 2.1 °C/hr; for the British WCG the decrease was from 2.6 °C/hr to 2.3 °C/hr; for the Tubing WCG the decrease was from 3.1 °C/hr to 2.7 °C/hr; for the Water Cooled Vest the decrease was from 1.2 °C/hr to 1.1 °C/hr. Thus, this 15 °C rise in air temperature decreases the change in mean body temperature per hour by about 10 to 20% depending on which WCG is worn.

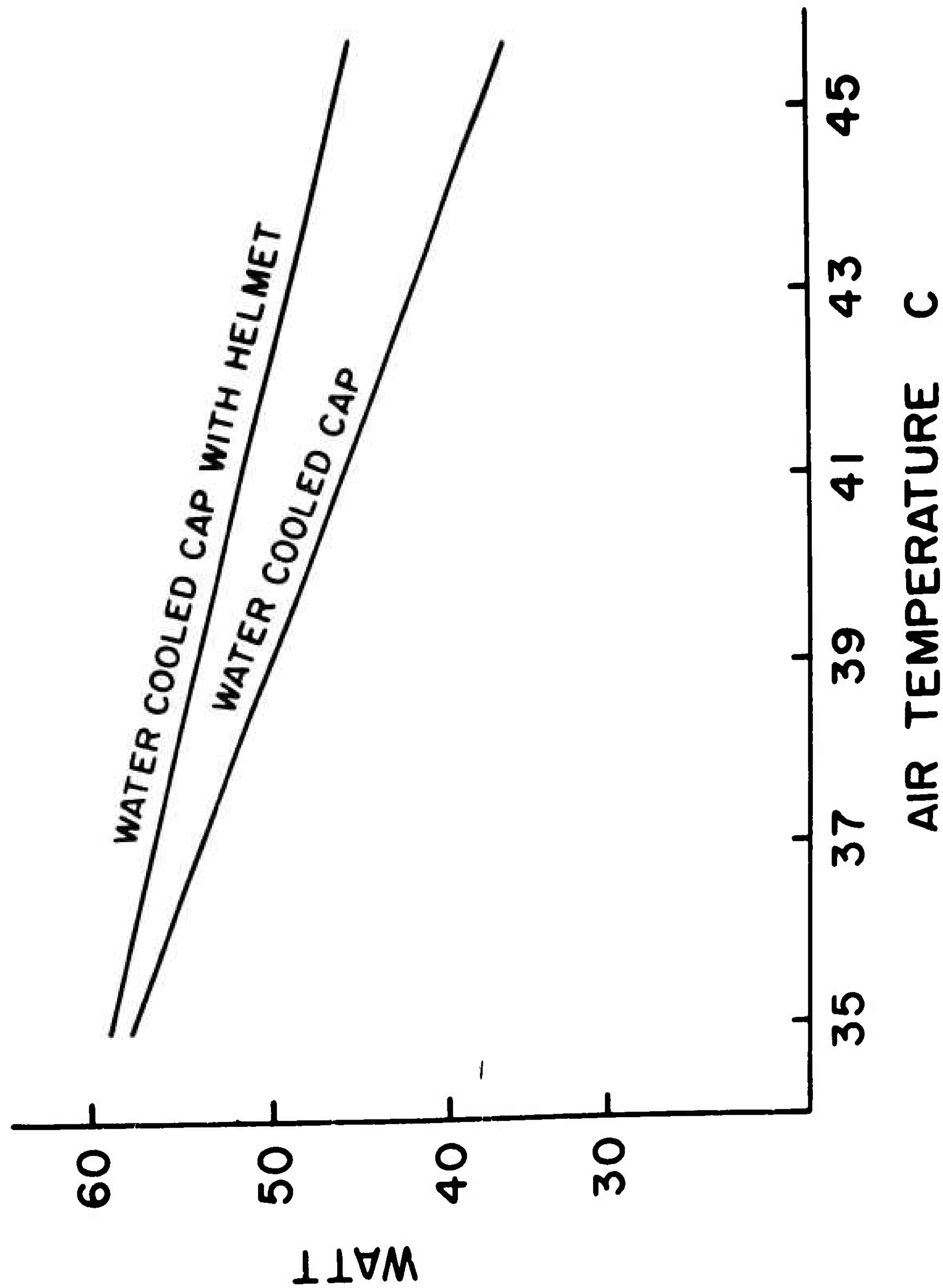
11. WATER COOLED CAP

The water cooled cap, although cooling only about 6% of the total body surface, could have application in cooling the head of a pilot who is exposed to the hot, humid environments in helicopters and aircraft. A water pump supplies the cooling fluid to the tubing of the water cooled cap and also passes the fluid through a heat exchanger containing a frozen canister (weight about 2.2 kg.) which had been kept overnight in the freezer compartment of a refrigerator. This cooling system was located in the chamber with the manikin during the experiment to simulate actual use in a hot environment.

Figure 3 shows that the quantity of cooling, in electrical watt supplied to the manikin's head, provided by the water cooled cap decreases continuously from the time when the canister is placed in the heat exchanger (0 minutes), with the steepest decrease in cooling occurring after about 90 minutes of cooling. The addition of an aircrew helmet, which fits tightly over the water cooled cap, apparently maintains



• WATER COOLED CAP
X WATER COOLED CAP/HELMET
50
40
30
20
10
0
WATT
0
30
60
90
120
HEAD COOLING TIME MINUTES
ΔT A-S = 0C
ΔT A-S = 8.3C


WATER COOLED CAP WITH HELMET
WATER COOLED CAP
WATT
60
50
40
30
35
37
39
41
43
45
AIR TEMPERATURE C

a closer fit of the water cooled cap over the manikin's head and also provides additional insulation (about a 30% increase in insulation over the head) to shield the water cooled cap from the chamber environment. Because of these two considerations, the heat transfer between the manikin's head and the water cooled cap is increased by up to 13 watt over the first 90 minutes of head cooling time when the helmet is worn.

The total potential for maximum heat removal (i.e. at time "0" minutes) under the experimental conditions of this study is shown in Figure 4 for a "sweating" head. Since practically all the evaporative heat transfer occurs over that portion of the head not covered by the water cooled cap (i.e. about 25% of the total head surface area) the addition of the helmet would have little effect on the evaporative heat transfer from the head. Therefore, the benefit obtained by wearing a helmet over the water cooled cap increases with increasing air temperature. At an air temperature of 47 °C and a relative humidity of 37%, the total heat removed from the head using this water cooled cap/helmet system would be about 42 watt. Under these environmental conditions, the quantity of heat removed from a head by the water cooled cap would equal about 1/3 of the metabolic heat production of a seated person. Recently, Williams (9) and Winckless (10) using water cooled hoods in similar high air temperature environments have measured respectively, 87 and 124 watt of heat removed from the head. Again, in the manikin experiment, no attempt was made to insulate the tubing or head from gaining heat from the hot environment.

12. DISCUSSION AND CONCLUSIONS

The problem of reducing heat stress in excessively hot environments (e.g. a wet bulb temperature greater than 34 °C) requires the wearing of some type of cooling garment. Usually, some insulation is worn over a cooling garment to maximize the contribution of the heat removed from the surface of a body to the total heat removed by a cooling garment. However, practically any added insulation increases the bulk and restriction to body movement, which could result in decreased human efficiency, in addition to that already caused by the cooling garment. Hence, in some circumstances, it may be a better approach to permit some loss in efficiency of a cooling garment by allowing it to be the primary means of isolating the body from the environment. An estimate of the energy cost of such an approach is that for each degree rise in ambient temperature above 35 $^{\circ}$C, the cooling available to remove the heat produced by metabolic processes decreases by 1 or 2 watt (the Apollo WCG decreases by 2.2 watt, the British WCG by 1.5 watt, the Tubing WCG by 1.8 watt, and the Water Cooled Vest by 0.6 watt). This amount of additional heat absorbed by the cooling water of a WCG comes from the air surrounding the tubing of a WCG and would have to be removed by the refrigeration unit supplying the cooling water to a WCG.

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